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Abstract: The impact of optical feedback on the direct performance of a monolithic InAs/GaAs quantum dot passively mode-locked laser intended for applications such as multi-gigahertz inter-chip/intra-chip clock distribution is experimentally investigated. Evaluation of the feedback resistance is an important feature, as the laser is to be monolithically integrated on chip with other devices, in which case optical isolation is difficult. This work shows that a feedback level on the order of -24dB is detrimental for mode-locking operation, enhancing noise in the RF electrical signal, strongly narrowing the useful mode-locking region as well as causing central frequency shift and severe instabilities.

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Monolithic mode-locked lasers (MLLs) have been suggested as compact, simple and reliable ultrashort pulse sources for a number of applications in communications, metrology, and, most recently, for clock distribution in future computer processors. [1,2] In the latter case, as the speed of microprocessors using electrical clock distribution keeps increasing and the silicon CMOS feature size shrinks, the speed bottlenecks due to RC delays and the increasing electrical power consumption on chips are expected to become serious problems.[3] As a consequence of that, MLLs are promising candidates for multi-gigahertz inter-chip/intra-chip clock distribution[3-5] because of their compact size, low power consumption, and direct electrical pumping. In a large number of these applications, performance of the laser in an external optical cavity is an important feature, as the laser is likely to be monolithically integrated on chip with other devices, in which case optical isolation is difficult. Quantum dots (QD), which have attracted a lot of interest in the last decade due to the charge carrier confinement in three spatial dimensions[6], are an ideal choice for the realization of semiconductor monolithic MLLs.[2,7] Desirable mode-locking characteristics such as ultra broad bandwidth, ultra fast gain dynamics, easily saturated gain and absorption as well as a low linewidth enhancement factor can be obtained with such nanostructures. In the latter case, a low linewidth enhancement factor is beneficial because it increases the tolerance to optical feedback of QD lasers as recently pointed out.[8] In various practical situations, MLLs may be subjected to optical feedback generated by discrete reflections. These perturbations may be induced by discontinuities in the optical waveguide of the monolithic chip or at the device-package interfaces from other optical devices placed along an optical fiber. A number of experimental studies have been performed so as to evaluate the sensitivity of MLLs under optical feedback. On one hand, resonant reduction of noise for external cavity lengths that are a multiple of the laser's optical length was observed.[9] On the other hand, by using quantum well (QW) based monolithic colliding-pulse passive MLLs, Passerini et al. have shown that optical feedback negatively affects the phase-locking relation between the longitudinal modes.[10] Finally, harmonic operation in MLLs subject to resonant feedback was also reported.[11] Recently, a numerical investigation has also demonstrated the influence of optical feedback on the dynamics of high-bit-rate MLLs.[12] A wide variety of dynamic regimes were numerically demonstrated taking into account the role played by the length of the external cavity in the MLL dynamics. Also the necessity to have a low linewidth enhancement factor was pointed out in order to get a wider stable mode-locking (ML) region. As no results have been reported except on QW MLLs, this paper aims to experimentally investigate the effects of optical feedback on the performance of a QD passive MLL operating at 10GHz. This work giving preliminary results shows that a feedback level on the order of -24dB is detrimental for ML operation, enhancing noise in the RF electrical signal, narrowing the useful ML region by several orders of magnitude as well as causing central frequency shift and severe instabilities when the device operates close to the coherence collapse regime.

The laser epitaxial structure of the device under study is a multi-stack Dots-in-a-WELL (DWELL) structure that is composed of an optimized six-stack QD active region grown by solid source molecular beam epitaxy on a (001) GaAs substrate. The two-section QD passive MLLs were fabricated with a total cavity length of 4.1-mm and a saturable absorber (SA) length of 0.8-mm. A highly reflective coating (~ 95%) was applied to the mirror facet next to the SA and the other facet was cleaved (~ 32%). Fig. 1 shows the measured light current characteristics for various SA reverse voltages. For the case in which the SA voltage source is left floating, the threshold current is found to be about 90mA at room temperature. When increasing the SA reverse voltage from 0V to 2V, the maximum output power progressively drops from 20mW down to 5mW because of a higher internal loss level in the cavity. As a consequence of that, the threshold current smoothly enhances from 110mA to 122mA when the SA reverse voltage is varied from 0V to 2V as shown in the inset of fig. 1.

The experimental setup to measure the feedback effects produced in the QD MLL is based on a 50/50 4-port optical fiber coupler. Emitted light was injected into port 1 using a single-mode lensed fiber. The optical feedback was created with a high-reflectivity dielectric-coated fiber (>95%) located at port 2. The feedback level was controlled via a variable attenuator and its value was determined by measuring the optical power at port 4 (back reflection monitoring, BRM). The effect of the optical feedback was analyzed at port 3 via a 10pm resolution optical spectrum analyzer (OSA) or a high-speed photodiode coupled to an RF electrical spectrum analyzer (ESA). A polarization controller was used to make the feedback beam's polarization identical to that of the emitted wave in order to maximize the feedback effects. The amount of injected feedback into the laser is defined as the ratio $\Gamma = P_1/P_0$ where P_1 is the power returned to the facet and P_0 the emitted one. The amount of reflected light that effectively returns into the laser can then be expressed as follows:[13]

$$\Gamma(\mathrm{dB}) = \mathrm{P_{BRM}(dBm)} - \mathrm{P_0(dBm)} + \mathrm{C_{dB}} \tag{1}$$

where $\mathrm{P_{BRM}}$(dBm) is the optical power measured at port 4, $\mathrm{C_{dB}}$ is the optical coupling loss of the device to the fiber which was estimated to be about -4dB and kept constant during the whole experiment. The stable bias condition for ML was investigated and the operating regime was recorded for different combinations of gain current and SA reverse voltage as depicted in fig. 2 (a). It is assumed that the ML condition, which is represented by the red dashed area, is fulfilled when the RF spectrum of the QD MLL exhibits peaks at the fundamental frequency and at least one higher harmonic. As shown in fig. 2(a), the ML region is found to be surrounded by two other regions related to sub-threshold and continuous wave (CW) operation. Even though the ML area decreases with increasing SA reverse voltage, this monolithic QD MLL generally exhibits a wider ML operating region compared to typical QW MLLs.[14] It is also noted that no self-pulsation was observed in the QD MLL described here. Self-pulsating devices have been shown to be very useful for many applications such as optical data storage systems (compact disc players) because they exhibit very low intensity noise characteristics e.g a reduced optical feedback sensitivity.[15] Fig. 2(b) shows the stable bias condition for ML under maximum optical feedback. Taking into account the mutual variations of P_{BRM} and P_0 in (1) as a function of bias current in the gain section, the maximum feedback rate is roughly maintained at Γ=-24 +/-1dB. In this case, the ML area is found to be reduced significantly; for instance, in the case of a 0V SA reverse voltage, the ML area is shrunk by a factor of ~50%. Compared to the case without optical feedback for which the device is mode-locked under the whole range of SA reverse voltages investigated, the ML condition in the presence of maximum optical feedback does not exist at greater than 1.2V. This large shrinkage of the ML condition is correlated with the SA reverse voltage because of a lower internal photon density within the cavity, which makes the device more sensitive to any external reflections. This result is in agreement with Passerini et al.[10] who have shown that the optical feedback negatively affects the mode-locking condition.

Fig. 3(a) shows the RF spectrum near 10 GHz without optical feedback when a 0V SA reverse voltage is considered and ~200mA DC forward current is applied to the gain section of the QD MLL. In the inset of fig. 3(a), the full span RF spectrum of the ML regime exhibits peaks at the fundamental frequency (~ 10GHz repetition rate) and the second harmonic. Fig. 3(b) shows next the RF spectrum under the same bias conditions but with the maximum optical feedback rate (Γ=-24dB). As seen in the figure, there is little change in the ESA spectrum compared to Fig. 3(a), which indicates that the device remains stable even under -24dB optical feedback rate;

Similar stable ML behavior extends from 180mA to 235mA as shown in fig. 2(b). Let us also stress that the optical feedback generates a positive shift of the fundamental frequency peak of about 1.5MHz. This shift was already reported in the case of a long external cavity for QW-based monolithic colliding-pulse passively mode-locked semiconductor lasers and is caused by a decrease in the refractive index caused by the plasma effect.[14]

Fig. 3(c) and Fig. 3(d) exhibit the RF spectra at the minimum (Γ=-40dB) and at the maximum (Γ=-24dB) optical feedback rates, respectively. The SA reverse voltage is tuned to 1V while keeping the DC forward current in the gain section at ~200mA. For the case in which optical feedback level is a minimum, the laser is still mode-locked making the behaviour of the device qualitatively similar to that of Fig. 2(a) in which no feedback is applied. However, under maximum optical feedback, 1V and 200mA bias conditions, residual peaks appear in the RF spectrum. The fiber-optic feedback loop generates external modes whose influence gets stronger when the SA reverse voltage is increased; thus, the mode separation of ~43MHz observed in Fig. 3(d) corresponds to a round trip time of 23ns, which agrees with the order of magnitude of the experimental setup's external cavity length. As shown in fig. 2(b), the ML area is strongly shrunk and extends from 235mA to 245mA only. Fig. 3(e) and (f) correspond to the same feedback conditions as previously stated, but now the SA reverse voltage is increased to 1.2V (still keeping the DC forward current in the gain section at ~200mA). For the minimum optical feedback level, the laser is still mode-locked which is close to the situation without optical feedback as shown in fig. 2(a). At the highest optical feedback rate for which the ML area occurs from 240mA to 245mA, severe instabilities arise in the RF spectrum; the noise level drastically increases and the spectrum linewidth gets much broader compared to the previous situations. This increase of the noise level can be induced when the device approaches the so-called coherence collapse regime.[16] This critical feedback regime can be seen as a transition to a chaotic state that is independent of the external cavity length and the feedback phase. The negative impact of the coherence collapse regime on MLLs leads to an enhancement of the RF spectral linewidth as previously pointed out.[10] The effect exhibited in fig. 3(f) does not represent the fully developed coherence collapse but does correspond to a feedback situation very close to this critical feedback regime since the external cavity modes are dominant and generate noise that negatively affects the phase locking condition. Let us stress that under this condition the positive frequency shift still occurs and is increased up to 3.2MHz. This frequency shift is expected to get larger when the MLL operates within the full coherence collapse regime.

Compared to the previous QW MLL results under feedback, the shrinking of the ML area is found to be less dramatic for the QD MLL reported here.[10] This difference might be due to a lower linewidth enhancement factor that helps to shift the coherence collapse regime towards higher feedback levels. As previously demonstrated for QW MLLs,[10,14] the coherence collapse is found to be of paramount importance in the ML degradation of QD lasers by negatively affecting the phase-locking relation between the longitudinal modes.

These results show an experimental comparison on the sensitivity to optical feedback in QD MLLs. This work shows that the deterioration of the RF spectrum is accelerated with the SA reverse voltage. This is mostly attributed to the occurrence of the critical feedback regime whose threshold decreases when the output power goes down.[17] The data presented here has demonstrated that mode-locking conditions can be significantly affected when the optical feedback rate is on the order of -24dB. Nonetheless, this level of feedback is considered relatively strong, and, thus, isolator-free operation of QD MLLs for such diverse applications as stable generation of RF signals or optical pulse trains for clocking is viable.

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Figure Captions:

Figure 1: Light current characteristics measured at room temperature for different conditions: SA voltage source is left floating (black) and for SA reverse voltages of 0V (grey), 1V (red) and 2V (blue). The figure in inset shows the threshold current as a function of the SA reverse voltage.

Figure 2: An operational map for combinations of the gain current and the SA reverse voltage. The ML condition is represented through the red dashed area. Sub-threshold and continuous waves (CW) regions are visible in-between.

(a) without external optical feedback

(b) under maximum optical feedback (Γ=-24dB)

Figure 3: RF electrical spectrum recorded for different configurations.

(a) RF spectrum without optical feedback when a 0V SA reverse voltage is considered and ~200mA is applied to the gain section. Full span RF spectrum of the ML regime is shown in the inset and exhibits the peaks at the fundamental frequency and at the harmonic component.

(b) RF spectrum under the same bias conditions as (a) but under the maximum optical feedback rate (Γ=-24dB).

(c) RF spectrum with minimum optical feedback (Γ=-40dB) when a 1V SA reverse voltage is considered and ~200mA is applied to the gain section.

(d) RF spectrum under the same bias conditions as (c) but under the maximum optical feedback rate (Γ=-24dB).

(e) RF spectrum with minimum optical feedback (Γ=-40dB) when a 1.2V SA reverse voltage is considered and ~200mA is applied to the gain section.

(f) RF spectrum under the same bias conditions as (e) but under the maximum optical feedback rate (Γ=-24dB).

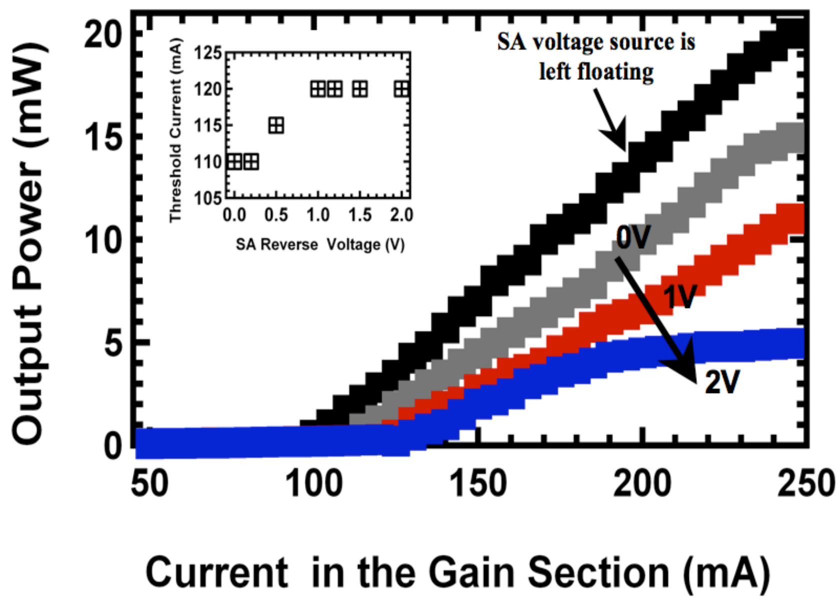


Fig. 1, F. Grillot et al.

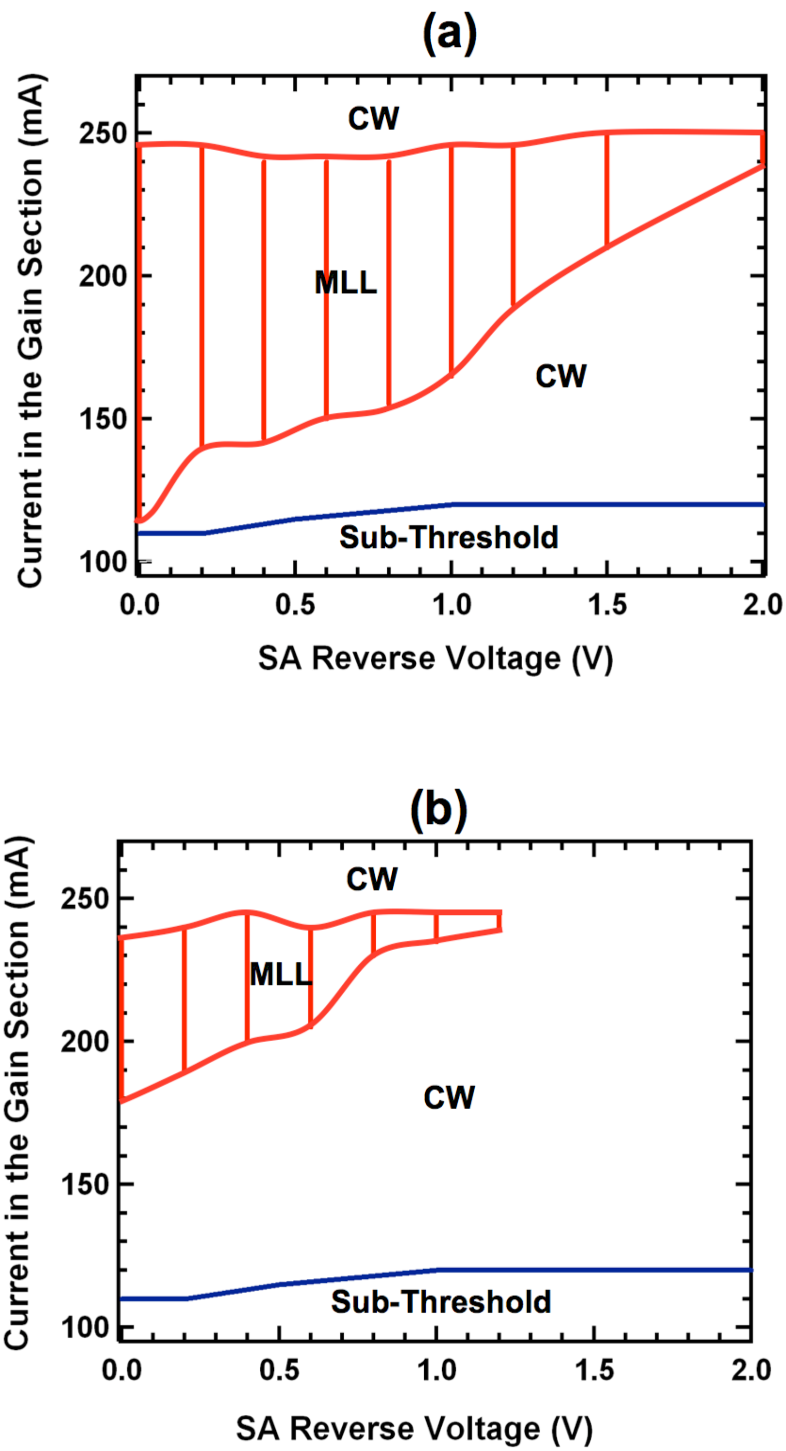
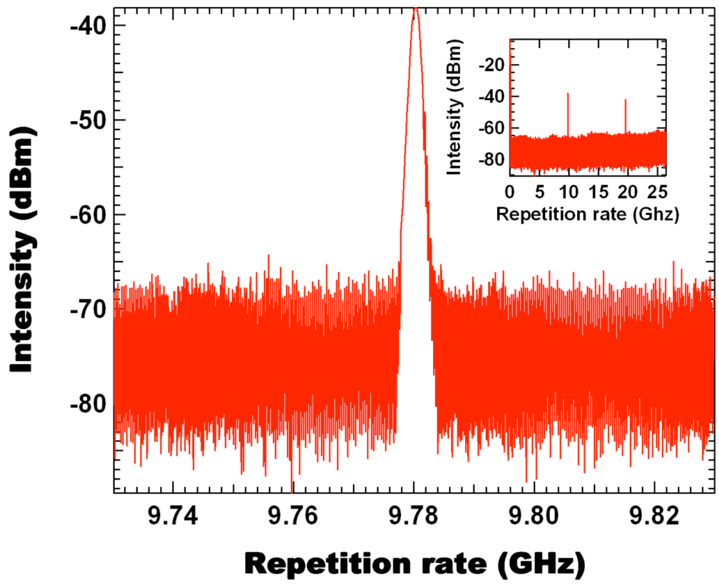
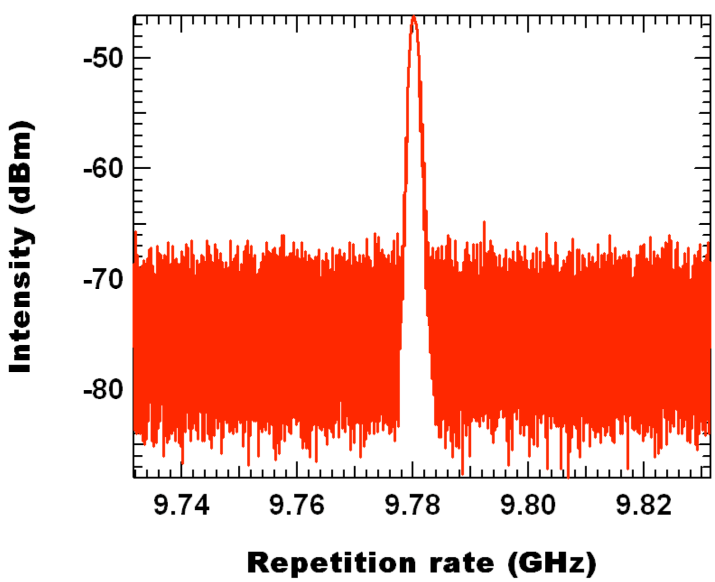


Fig. 2, F. Grillot et al.

(a)


-40
-50
-60
-70
-80
Intensity (dBm)
9.74
9.76
9.78
9.80
9.82
Repetition rate (GHz)
-20
-40
-60
-80
Intensity (dBm)
0 5 10 15 20 25
Repetition rate (Ghz)

(b)


-50
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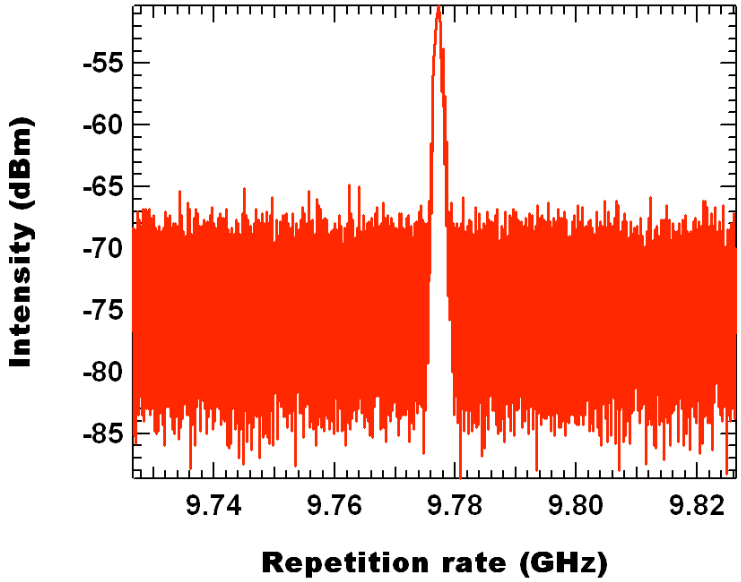
Intensity (dBm)
9.74
9.76
9.78
9.80
9.82
Repetition rate (GHz)

(c)


-55
-60
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-85
Intensity (dBm)
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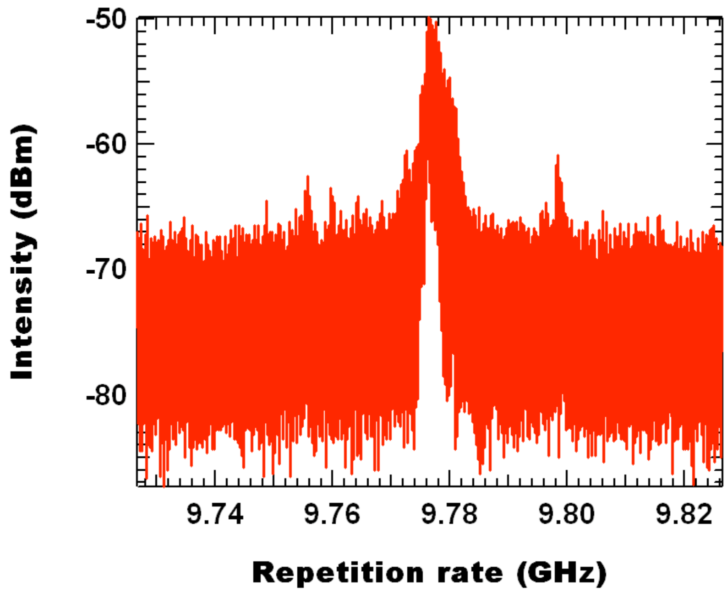
9.82
Repetition rate (GHz)

(d)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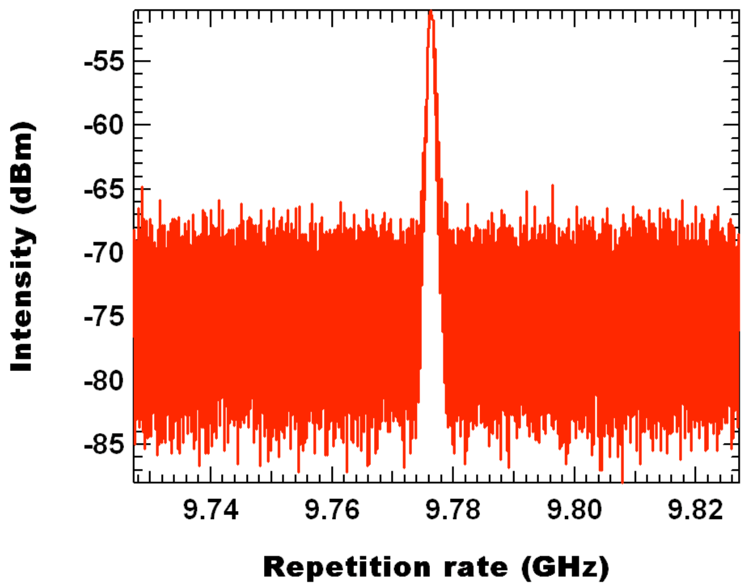
Repetition rate (GHz)

(e)



(f)

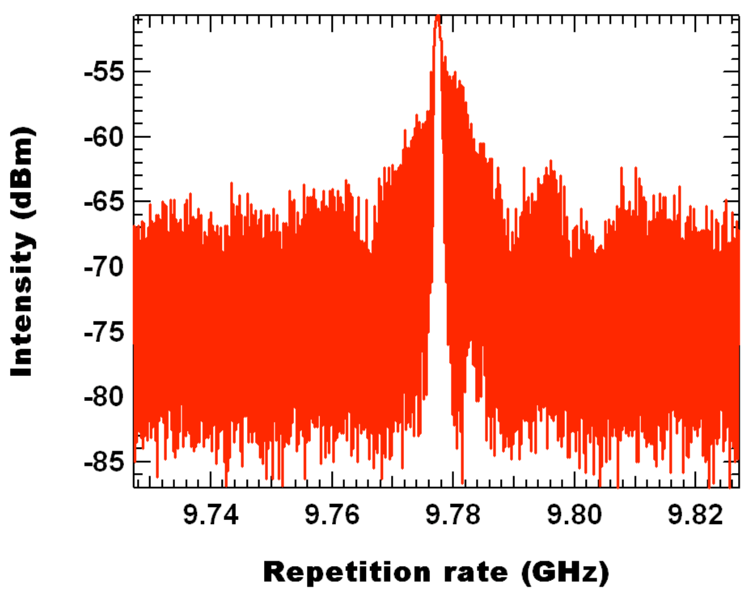


Fig. 3, F. Grillot et al.